Chapter 4

Development Prospect of Gas Insulation Based on Environmental Protection

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Additional information is available at the end of the chapter

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Abstract

The research situation of environmentally friendly gas insulation is expounded in this paper. The basic physical and chemical properties of the insulating gases are analysed, to propose several environment-friendly insulating gas of potential alternative to sulphur hexafluoride (SF_6). The insulation characteristics of different components gas mixtures with 90% of nitrogen (N_2) and carbon dioxide (CO_2) as buffer gas and 10% octafluorocyclobutane (c-C_4F_8), Trifluoroiodomethane (CF_3I) and heptafluorobutyronitrile (C_4F_7N) as the main insulating gas had been tested with 5–20 mm sphere-plane electrode gaps in non-uniform electric field under the power frequency voltage and positive and negative lightning impulse breakdown. The development prospects of environmentally friendly gas insulation are forecasted. Further analysis of c-C_4F_8,CF_3I and C_4F_7N (some friendly gases, which have the potential to replace SF_6) are conducted trying to points out the further research direction.

Keywords: electrical equipment insulation, environmentally friendly gases, alternatives gases, SF_6

1. Introduction

Because of its good electrical insulating properties, sulphur hexafluoride (SF_6) can satisfy the insulating demands of the electrical apparatus. SF_6 is nontoxic and non-combustible, which guarantees the security of its application in the gas insulating apparatus. What is more, the chemical properties of SF_6 are stable and it can be compatible with most mental and solid insulating materials. There is little decomposing by-products after discharge or arc, which guarantees the following insulating function and protects apparatus. Nowadays, SF_6 has been an important industrial gas with more than 20,000 tons' produced every year all over the world, and 80% of that is applied as insulating gas in electrical apparatus [1]. With the continuous increase of China's electrical demand and the expansion of the electrical grid, the demand for insulating gas will continuously increase [2–4].

Although the characteristics of SF_6 can satisfy the requirements as insulation gas in electrical apparatus, such as gas-insulated substations, scientists have recognised that it can influent and aggravate the greenhouse effect in recent years. SF_6 is a strong greenhouse gas that will cause serious harm to the environment. The Global Warming Potential GWP of SF_6 is 23,900 times stronger than that of CO_2 [5], which means that under the computing period of 100 years. Far more serious is that because of the extremely stable chemical properties, it is very hard to decompose SF_6 in nature and it can exist for 3200 years in atmosphere [6], which will make the environmental influence and greenhouse effect continuously accumulated.

In the *Kyoto Protocol to the United Nations Framework Convention on Climate Change* signed in 1997 in Kyoto of Japan [2], SF_6 was regarded as one of the six-kinds of greenhouse gas (CO_2,CH_4,N_2O,PFC,HFC and SF_6) and it demanded that developed countries should stop and reduce the total emission of greenhouse gas. With signing the *Paris Agreemen*t [3], international society are making efforts to reduce carbon emissions, which means that the application of SF_6 in industry will be limited more and more [4, 5, 7]. Therefore, researching new method of gas insulating to replace SF_6 becomes an urgent work.

It is important to look for environmentally insulating gas with similar insulating characteristics and physicochemical properties of SF_6 to replace SF_6. SF_6 belongs to inorganic fluorinated gases, and its molecular geometry is octahedron with six-fluorine (F) atoms in outer surface and one sulphur (S) atom in centre. Because of fluorine belongs to the halogens, its peripheral electronic layer is occupied by seven electrons and can become stable structure with one more electron, which allows it to strongly attract electron. Moreover, in the molecule of SF_6, F atoms and S atom form more stable covalent bonds by sharing electrons. However, F atoms also have the trend to attract electrons so that the entire molecule has a trend to attract electron. Therefore, it has better insulating characteristics than other gaseous molecular without electronegativity. In addition, although the gas characteristics showed by the structure of macro element cannot show the insulation strength of gas exactly, even counterexample existing, researchers have attached importance to that and the researching emphasis of alternative gas is concentrated on the halogenated gas [8]. In 1997, the research report about the insulation characteristics and arc quenching of alternative gas of SF_6 written by the National Bureau of Standards of the U.S.A [9] introduced many potential alternative gases. Besides, in this work was studied the breakdown voltage under direct current (DC) uniform field of gases, such as organic fluorinated ones, compared with SF_6, and this comparison is shown in **Table 1**. The result of the report shows that most fluorinated gases have good electronic adsorption, which it is related to the addition of fluorine, but not all the organic fluorinated gases have good insulation characteristics. Besides, it is not correct to evaluate the insulation characteristics just based on the elements that constitute a gas, so it is necessary to analyse different gases in detail for comparison. Because the physicochemical properties of octafluorocyclobutane ($c\text{-}C_4F_8$) are close to SF_6, its cost is low and Greenhouse Warming Potential (GWP) is lower than SF_6, the report has specially indicated that $c\text{-}C_4F_8$ and its mixture can be the study subject for long time [10], so that researchers are focused on the study of this gas.

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Gas	Relative breakdown voltage	Remarks
SF_6	1	As reference of gas Relative breakdown voltage is 1
C_3F_8	0.90	With strong absorption to free electron, especially low-power free electron
c-C_4F_8	About 1.35	
2-C_4F_8	About 1.75	
1,3-C_4F_6	About 1.50	
Hexafluorobutadiene (2-C_4F_6)	About 2.3	
CHF_3	0.27	With weaker absorption to free electron
CF_4	0.39	

Table 1. Relative direct current (DC) breakdown voltages of some fluorination gases [1, 8, 12].

Besides c-C_4F_8, organic halogenated gas, trifluoroiodomethane (CF_3I), contains fluorine (F) and iodine (I) has been concentrated by researchers for its much lower GWP and better insulation characteristics. At the same time, ALSTOM company in France and 3M company in US produce an electrical insulation gas mixtures together, named G3, whose main ingredient is heptafluorobutyronitrile (C_4F_7N), a kind of fluorinated nitrile with Novec 4710 as trade name [11]. Besides, ABB company produces electrical insulation gas mixtures whose main ingredient is fluorinated ketone such as Heptafluoropropyl trifluorovinyl ether ($C_5F_{10}O$) and Undecafluorohexanoyl Fluoride ($C_6F_{12}O$). Properties of some potential alternative gases to SF_6 are shown in **Table 2**.

Gas	Physicochemical properties		Environmental characteristics	Electrical characteristics	
	Toxicity	Boiling point (unit: °C)	Relative GWP	Relative insulation characteristics [15]	Relative rising rate of recovery voltage (RRRV) characteristics
SF_6	Nontoxic	−64	1	1.00	1.00
CF_3I	Low-toxicity	−22.5	≈0	1.20	0.90
c-C_4F_8	Nontoxic	−6	0.3	1.30	—
g^3(C_4F_7N/CO_2)	Low-toxicity	24 (Pure)	0.02	0.85–1	—
$C_5F_{10}O$/air	Nontoxic	26.9 (Pure)	≈0	0.75–0.85	—
Hexafluoropropylene (C_3F_6)	Toxic	−29.6	≈0	1.01	—
Fluorinated 1,3-butadiene (C_4F_6)	Toxic	6~7	≈0	1.4	—
Fluorinated 2-butyne (C_4F_6)	Toxic	−25	≈0	1.7	—
Fluorinated 2-butene (C_4F_8)	Toxic	1.2	—	1.8	

Table 2. Properties of potential alternative gas to sulphur hexafluoride (SF_6) [8, 13, 14].

2. Analysis of potential alternative gas

2.1. Octafluorocyclobutane (c-C_4F_8)

Octafluorocyclobutane, c-C_4F_8 is an important industrial gas. Nowadays, it is used in plasma etching technology or as refrigerant [16]. Similar to SF_6 gas, the performance to absorb electron easily of fluorine in c-C_4F_8 is shown in the characteristics of the whole molecule, so that c-C_4F_8 has a stronger absorption to free electron. c-C_4F_8 is colourless, odourless, nontoxic to human bodies at low concentration, non-combustible, nonexplosive and with GWP of about 8700 relative to CO_2. Though it belongs to greenhouse, but in the same conditions, its negative effects are just one third of SF_6 [17]. In addition, as organic halogenated gas, c-C_4F_8 does not contain chlorine or bromine, so it is not harmful to the ozone layer. The molecule of c-C_4F_8 is circular with a stable chemical structure and does no harm to other solid materials in electrical apparatus, such as aluminium alloy, copper contact and epoxy supporting insulators. Recently, the price of c-C_4F_8 differs with the purity of gas. The price of this gas with 99.9% purity is about 200 RMB/kg [8] (1 RMB ≈ 0.16 dollar≈0.13 euro, the same below), as the price of gas with 99.999% purity is about 500 RMB/kg, and that has obviously reduced compared with the price of about thousand RMB per kilogramme 10 years ago. This is related to more applications, such as refrigerant [18], that are using c-C_4F_8 and the rise of production. Nowadays, the price of c-C_4F_8 is only a little bit higher than that of SF_6, but if c-C_4F_8 is applied widely in electrical domain, its price still can be reduced, so the cost is not the obstacle to be applied in electrical apparatus.

Long before, Japanese researchers began to research the electrical properties of c-C_4F_8 and indicated that it had the feasibility to replace SF_6 in electrical apparatus. Then, the researchers of plasma and electric-related domains from the U.S.A. and Mexico began to use Boltzmann equation, calculation of parameter of discharge particle and breakdown test to research the insulation characteristics of c-C_4F_8. Shanghai Jiao Tong University, Xi'an Jiao Tong University and other high schools in China began the researches about calculation of academic simulation and breakdown test of c-C_4F_8. The results of researches have shown that the insulation characteristics of pure c-C_4F_8 are better than SF_6, in air pressure at 0.3 MPa and over. The breakdown voltage of the gas mixtures of c-C_4F_8 and N_2 or CO_2 is higher than the gas mixtures of SF_6 with the same contents, and in low air pressure or atmospheric pressure, the breakdown voltage of the gas mixtures of c-C_4F_8 can approach the gas mixtures of SF_6 with the same contents. In conclusion, c-C_4F_8 and its gas mixtures have similar insulation characteristics with SF_6, and the breakdown voltage differs a little with the composition, mixture ratio and gas pressure, so it can satisfy the demands of actual application.

The relative molecular mass of c-C_4F_8 is 200, higher than that of SF_6 (146.06), and it means that the condensing temperature of c-C_4F_8 will be high, is about −6°C, higher than −63.6°C of SF_6. The insulating gas should exist in gaseous state in the electrical apparatus, thus need to have a low enough liquefaction temperature. One way to reduce its liquefaction point is to add some buffer gas including nitrogen (N_2) or carbon dioxide (CO_2), which may lead to a weaker insulation strength. So we need to take a balance between the low liquefaction temperature and good insulation property when considering the mixture ratio for c-C_4F_8

gas mixtures. Therefore, c-C_4F_8 is not suited to be applied in apparatus as pure gas, or it cannot satisfy the demand of arctic alpine regions. Thus, it should be mixed with other gas in some ratios to reduce the condensing temperature of the gas mixtures and be used as gas mixtures.

2.2. Trifluoroiodomethane (CF_3I)

Trifluoroiodomethane (CF_3I) is colourless, odourless, non-combustible and nonexplosive. CF_3I is a new industrial gas that can be used as an environmental refrigerant and alternative fire-extinguishing agent. It can be used as additive or mixed composition to replace traditional refrigerant Freon and fire-extinguishing material "Halon." Because its GWP is very low, about 1–5 relative to CO_2 is much lower than most organic halogenated gases, so its influence on greenhouse is very small. At the same time, it does not contain chlorine and bromine that is commonly present in most refrigerants, so it will not damage the ozone layer, thus the United Nations regards it as new refrigerant to replace Freon [19]. This can prove that CF_3I is a kind of environmentally friendly gas, and has related basis in industrial application. As a kind of fire-extinguishing material, its efficiency is outstanding and has little negative influence on environment, and it is well compatible with normal industrial materials, so that it will not cause chemical reaction or erosion. Therefore, it has passed some related standards of the U.S.A [20]. and can be used in aerospace and other areas. In addition, it can rise the security of the electrical apparatus by applying CF_3I in electrical apparatus such as cubicle gas insulating switchgear (C-GIS) or compact transformer. It is especially appropriate to be used in populous regions of central city in order to reduce the conflagration or explosion caused by the bug of electrical apparatus. The molecular structure of CF_3I is shown in **Figure 1** RMB. It is affected by halogens such as F and I, so it has strong absorption to free electron. So that it can absorb free electron at the beginning of discharge when electron avalanche forms, and then it can restrain the formation of collision ionisation, which enhances its insulation property. What is worthy to indicate, that the difference between CF_3I and SF_6, as well as c-C_4F_8, comes from the asymmetry of its structure, which makes the polarity effect of the molecule stronger. The three-F atoms in the molecule has stronger absorption to electron than I atom, so the electron cloud in the molecule trends to F atoms, and the density of the electron cloud around the carbon-iodine covalent bond formed by I atom and carbon (C) atom is reduced, and the energy barrier to absorb electron is also reduced. Therefore, the whole molecule has a strong ability to absorb electron.

Because of CF_3I is a new industrial gas, its application in China is not widely extended, the production in China is low. Currently, CF_3I produced in China costs about 2000 RMB/kg, the price is much higher than SF_6 [1]. The main reason why the price of CF_3I in China is higher than that for SF_6 [1] is that the demand is very low. According to the producers of CF_3I (Beijing Yuji Science & Technology Co., Ltd.), after CF_3I will be used widely and will be mass-produced, the constant cost of CF_3I will reduce a lot with the actual cost lower than 600 RMB/kg. Moreover, by optimising and upgrading, its price will be reduced continuously like that for c-C_4F_8.

Since year 2000, many researchers in China and abroad begin to research this new insulating gas [21, 22]. Researchers of plasma from Mexico have calculated and measured the ionisation

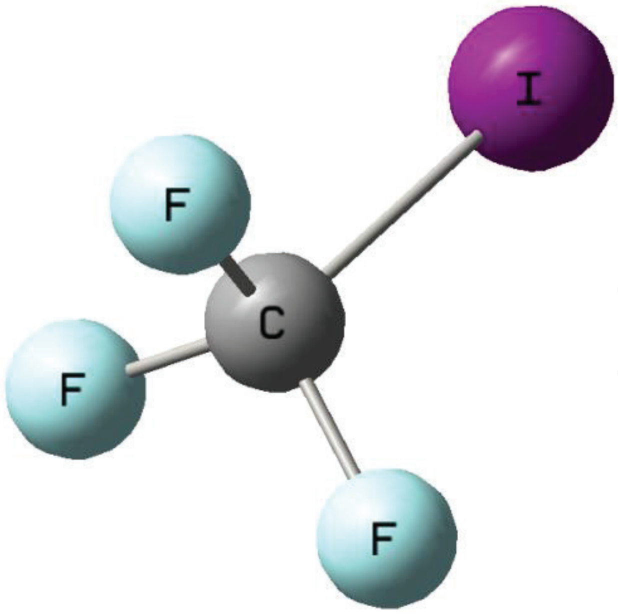

Figure 1. Molecule structure of CF_3I.

coefficient, attachment coefficient and electron drift velocity during the process of discharge of CF_3I and its gas mixtures with N_2, SF_6 and other gases [23, 24]. The aforementioned work has quantified the reaction between free electron and gas molecule during the process of discharge, and has analysed the insulation strength of gas mixtures from the perspective of the parameters of discharge. Tokyo University of Japan, Tokyo Denki University and Japan Electric Power Company have researched CF_3I by testing [25, 26]. They make the breakdown test to CF_3I and its gas mixtures with N_2, CO_2 and air by using lighting impulse. The results show that the insulation strength of pure CF_3I is better than that in SF_6, about 1.2 times than SF_6, and CF_3I-CO_2 gas mixtures with high content also has better insulation characteristics to be able to replace SF_6. Many universities and academies in Europe also research the gas mixtures of CF_3I-CO_2 and CF_3I-N_2 in different conditions [24]. The results show that the positive synergistic effect of the gas mixtures of CF_3I and N_2 is less obvious than that of the gas mixtures of SF_6 and N_2, which means that in the same mixture ratio, the insulation strength of the gas mixtures of CF_3I-CO_2 cannot increase with the rising content of CF_3I because of the synergistic effect [22]. In addition, the gas mixtures of CF_3I and CO_2 with low content show better positive synergistic effect. Shanghai Jiao Tong University, Xi'an Jiao Tong University and Chongqing University in China has researched CF_3I and its gas mixtures by academic calculation and testing research [27–29]. Shanghai Jiao Tong University uses Boltzmann's equation to calculate and analyse the discharge parameters and insulation characteristics of the gas mixtures of CF_3I and N_2, CO_2, He and so on and get the alternating current (AC) breakdown voltage in non-uniform electric field and slightly non-uniform electric field by testing [28, 30]. Other researchers have measured partial discharge voltage and other insulation characteristics of the gas mixtures of CF_3I [31, 32]. The results show that CF_3I has good electrical insulation characteristics, but the positive synergistic effect of the mixture of CF_3I and normal buffering gas is not obvious, so that the insulation characteristics of its gas mixtures are lower than SF_6. Therefore, the research about the synergistic effect of CF_3I and other gas is the key to be applied in the future.

2.3. Fluorinated nitrile gas and G3 gas mixtures

ALSTOM company in France and 3M company in U.S.A. have joined to research the alternative to SF_6 gas. Among many organic fluorinated gases, they choose the gas, which is also alternative refrigerant, and organic chemical compound that contains four-C atoms and seven-F atoms, with a trade name of Novec 4710 [11] and chemical formula of C_4F_7N, named G3. Besides, its molecular structure is shown in **Figure 2**. The gas has replaced a fluorine atom with nitrile group ($-C\equiv N$) on the basis of the fluorinated hydrocarbon gas, and becomes fluorinated nitrile gas. This nitrile group containing carbon-nitrogen triple bond has a special chemical structure to make C_4F_7N have very good insulation performance, which can reach about two-times of that of SF_6. The chemical features of this gas are similar to the organic fluorinated gas with stable chemical characteristics and can be well compatible with other materials used in electrical assets. The relative molecular mass of C_4F_7N is 195, with a high condensing temperature of −4.7°C, so that it cannot replace SF_6 as a single gas, it should become gas mixtures with buffering gas such as N_2 or CO_2. Because of it is a new insulating gas, related testing research is lacking. According to research result obtained by now, the insulation characteristics of its gas mixtures with CO_2 is about 90% of the SF_6 mixtures with the same amount of CO_2, and this gas can also be used as arc quenching medium being applied in circuit-breakers [33]. Nowadays, this gas is researched and produced by 3M company and its cost is dozens of times higher than other gases [33], so the cost is one of the obstacles for its industrial application. With the accomplishment of the production technology of the gas and the development of the producers at home, the price could be reduced.

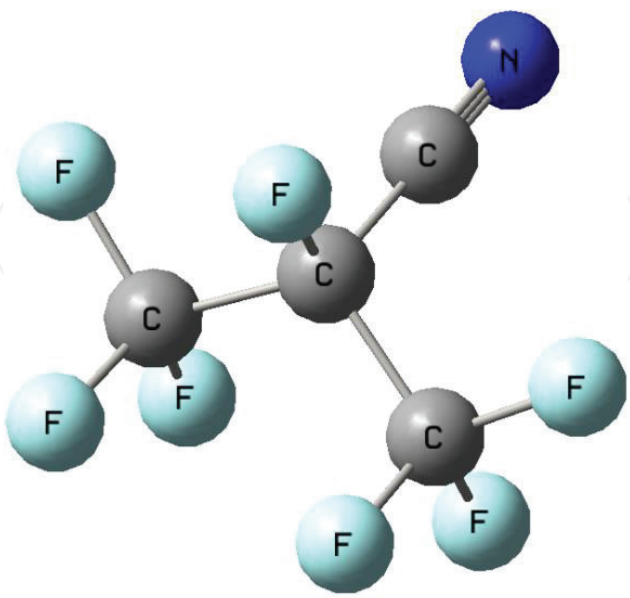

Figure 2. Molecule structure of C_4F_7N.

The gas with the chemical formula of C_4F_7N has two-isomeric compounds, their chemical formulas and element compositions are the same, but for the different positions of nitrile groups, their molecular structures and microcosmic natures are different. For Novec 4710 gas used in G3 gas, its nitrile group is located in the carbon atom in the middle of the organic carbon-chain, and the other isomeric compound has a nitrile group located in the carbon atom at one end of the carbon-chain, which constitute a virulent gas that cannot be used in industry. In addition, during the production of Novec 4710, by avoiding the production and the mixture of the virulent isomeric compound is key to apply this gas in a real environment. What is more, any gas will be decompounded to produce decomposed by-products in the condition of high temperature and pressure during the discharge process. Moreover, it should be continuously researched about how to guarantee that this gas will not produce toxic isomeric compounds or other gases during the process of discharge or arc interruption.

2.4. Fluorinated ketone gas

ABB company in Switzerland has supported a method for evaluating the greenhouse effect of SF_6 [34, 35], and it is to take advantage of fluorinated ketone gas as the main ingredient of gas mixtures, which contains organic fluorinated gas with carbonyl group ($C{=}O$) such as $C_5F_{10}O$ and $C_6F_{12}O$. This kind of gas is similar to fluorinated nitrile gas. It is a chemical compound, which uses the carbonyl group to replace one F atom of fluorinated hydrocarbon based on fluorinated hydrocarbon. Because of carbonyl group has carbon-oxide double bond, which is unsaturated bond as the same as the carbon-nitrogen triple bond, it has good absorption to free electron, and it shows higher insulation characteristics in macro-performance [36]. According to the existing testing data in China and abroad, the insulation characteristics of pure $C_5F_{10}O$ and $C_6F_{12}O$ are about two-times higher than SF_6 and their GWP value approaches zero, physicochemical properties are stable and they have good compatibility with materials and industrial applicability. The fluorinated carbonyl, which ABB has applied in the gas mixtures has more than five-carbon atoms, so its relative molecular mass is bigger than other insulating gases, such as $C_5F_{10}O$ with 266 and $C_6F_{12}O$ with 316. Besides,the condensing temperature of $C_5F_{10}O$ and $C_6F_{12}O$ is very high with 24 and 49°C at room condition, which means that they are liquid at normal temperature and gas pressure. Therefore, this gas cannot be used in any electrical insulating domains as single gas, and it can only be applied as gas mixtures. Limited by its high-condensing temperature, it will have low content in the gas mixtures, which causes the limitation of the insulation strength of the whole gas mixtures, so the synergistic effect of this gas and other gas mixtures is very important. Therefore, the use of this kind of gas forming gas mixtures, which allows it keep high insulation characteristics at low concentrations, is the emphasis of research in the future.

3. The power frequency AC breakdown characteristics of the c-C_4F_8, N_2, CO_2 gas mixtures

The breakdown voltage under AC voltage of the gas mixtures with a constant content of 10% of c-C_4F_8 and different content of N_2 and CO_2 has been measured by testing. **Figures 3** and **4** show the variety of the AC-breakdown voltage and maximum electric strength of the c-C_4F_8, N_2, CO_2 gas mixtures with the variety of gap distance under different air pressure. The gas discharge test chamber and other internal structure are the same with that in Ref. [37]. The method to inflate gas mixtures to test chamber is introduced in Ref. [17]. The gases tested in the present paper are listed in **Table 3**.

From **Figures 3** and **4**, it can be observed that the behaviour of c-C_4F_8 mixtures is similar to the SF_6 gas mixtures, the AC-breakdown voltage of the c-C_4F_8, N_2, CO_2 gas mixtures gets higher values as the gap distance gets bigger, and it shows saturation effect. The maximum electric strength of the gas mixtures gets lower values as the gap distance gets bigger, and it shows that the gas mixtures has some sensitivity to the non-uniformity of the electric field. As the non-uniformity of the electric field increases, the maximum electric field able to be tolerated reduces, and the trend of change is similar to SF_6, N_2 and CO_2 in Appendix **Figures A1** and **A2**.

Figure 5 shows that under different gap distances, the variety of the AC-breakdown voltage of the c-C_4F_8, N_2, CO_2 gas mixtures as the gas pressure changes. The AC-breakdown voltage of c-C_4F_8 gas mixtures increases linearly as the air pressure increases without hump effect, and this trend is the same to SF_6 gas mixtures. From **Figures 3**–**5**, we can see that the variety of the breakdown voltage of the c-C_4F_8 gas mixtures with the same content as the air pressure and the electrodes gap changes is the same to SF_6 gas mixtures. However, the curves of breakdown voltage of c-C_4F_8 gas mixtures with different contents in the graphs are more concentrated than SF_6. That is to say, the breakdown voltages of gas mixtures have little difference with different contents, at the same time, it shows that the breakdown voltage of the gas mixtures of c-C_4F_8 and CO_2 is the highest and the gas mixtures with N_2 is lower, this is different from the properties of SF_6 gas mixtures. When the gap distance is 20 mm, the AC-breakdown voltage of 10%c-C_4F_8+90%CO_2 is about 10% higher than that of 10%c-C_4F_8+90%N_2.

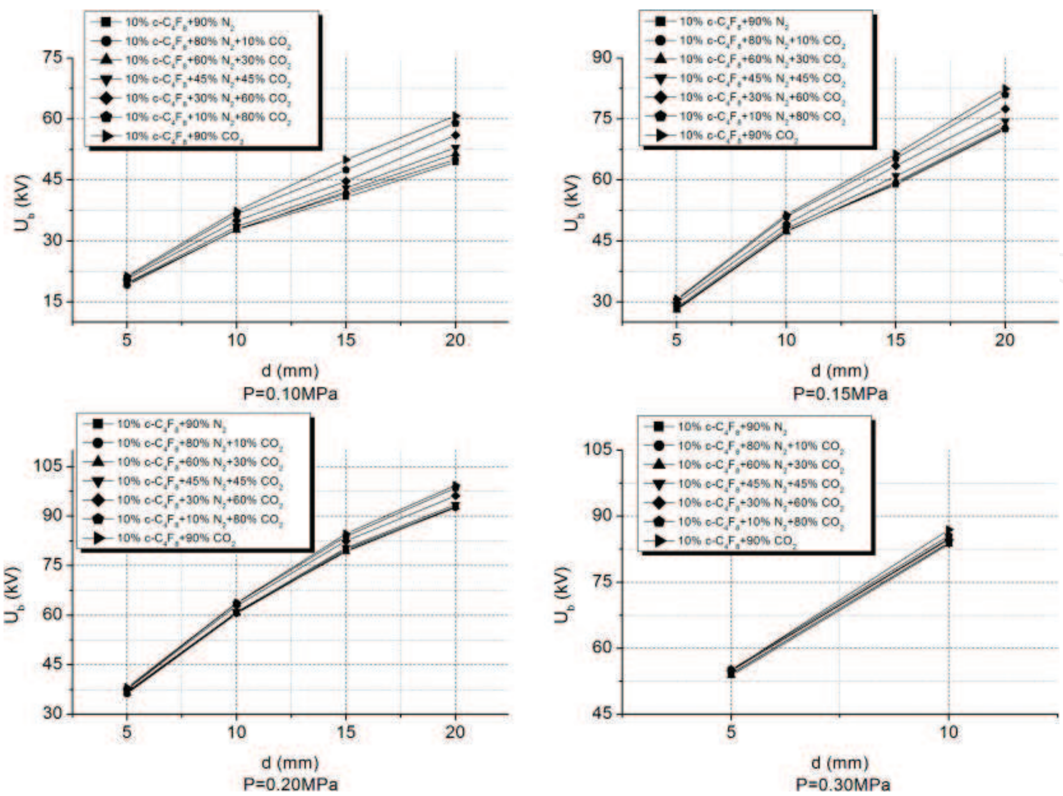

Figure 3. AC-breakdown voltage of c-C_4F_8, N_2, CO_2 gas mixtures with different gas pressures.

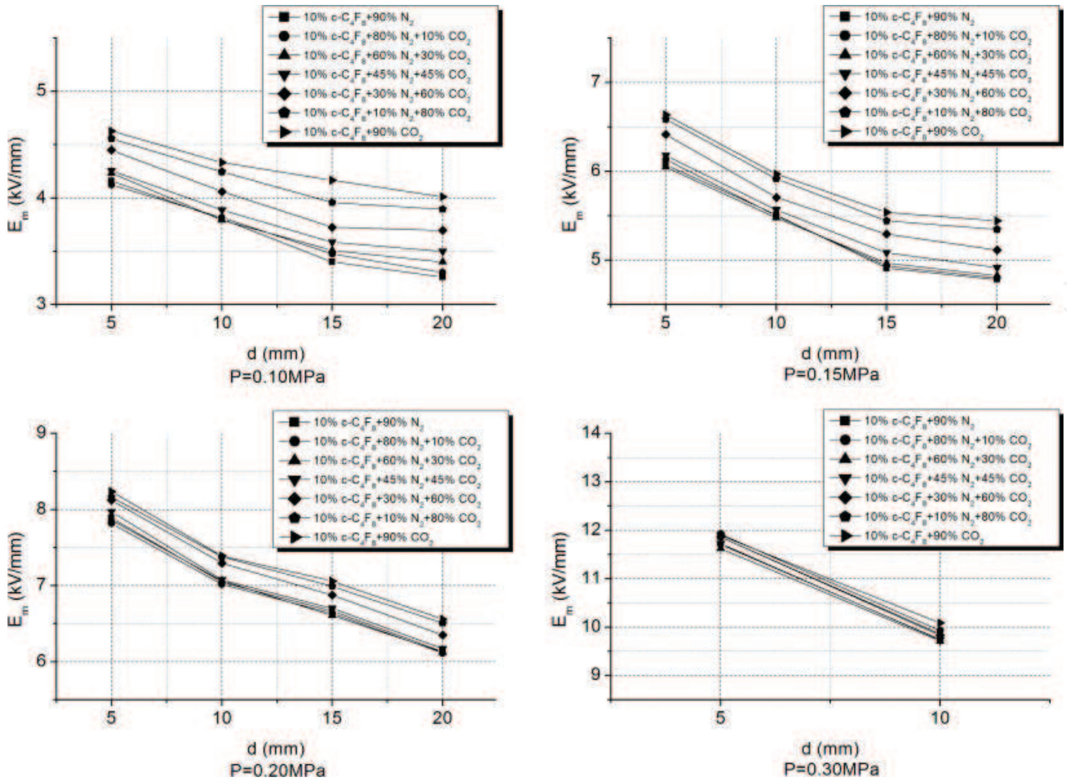

Figure 4. Maximum electric strength of c-C_4F_8, N_2, CO_2 gas mixtures with different gas pressures.

Number	c-C_4F_8/CF_3I mixing ratio (%)	N_2 mixing ratio (%)	CO_2 mixing ratio (%)
1	10	90	0
2	10	80	10
3	10	60	30
4	10	45	45
5	10	30	60
6	10	10	80
7	10	0	90

Table 3. Test gas mixtures for power frequency AC breakdown experiments.

Figure 6 shows under different gas pressures, the variety of the AC-breakdown voltage of the c-C_4F_8, N_2, CO_2 gas mixtures as the content changes. If it is make the gas mixtures of 10%c-C_4F_8 + 90%N_2 as the initial matched group, it can be seen that the breakdown voltage of the gas mixtures increases as the content of CO_2 increases, and when the content of CO_2 exceeds 60%. In other words, with a content of N_2 lower than 30%, the increase of the breakdown voltage is more noticeable.

Because of during the process of discharge, N_2 will make the ionisation probability of CO_2 increase as well, when reducing N_2 and increasing CO_2 of the c-C_4F_8 gas mixtures, the breakdown voltage of the triple gas mixtures in **Figure 6** does not has an obvious increase

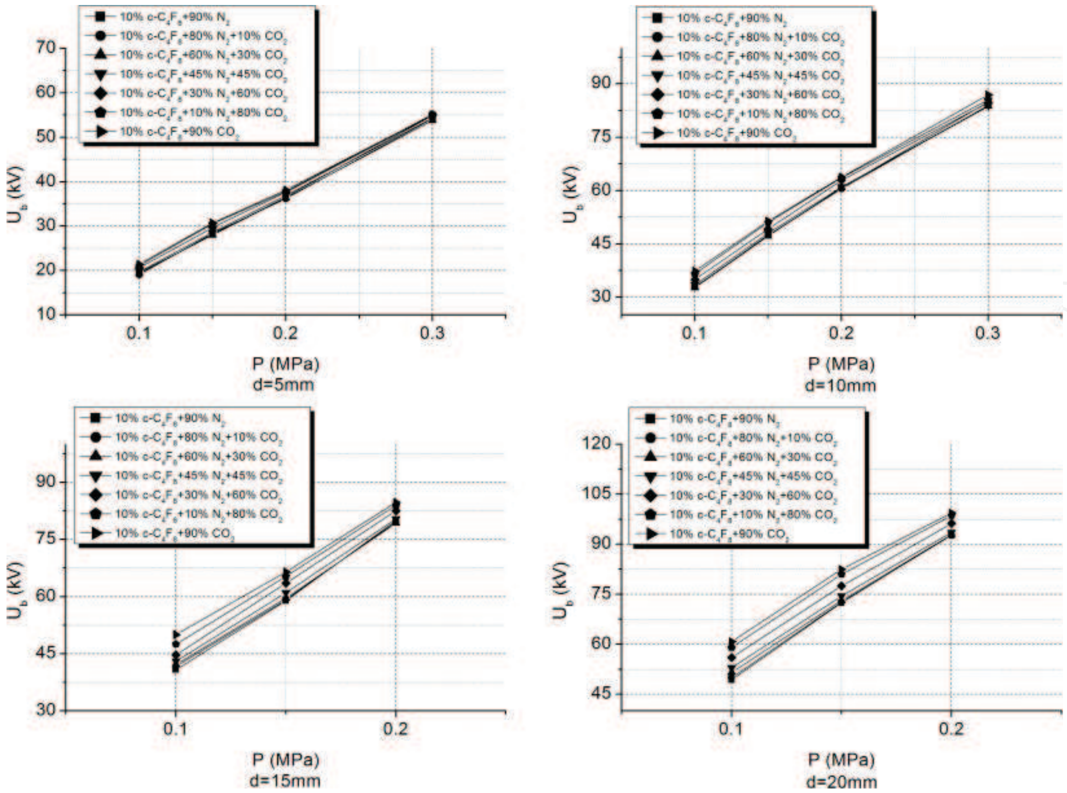

Figure 5. AC-breakdown voltage of c-C_4F_8, N_2, CO_2 gas mixtures with different electrodes gap distances.

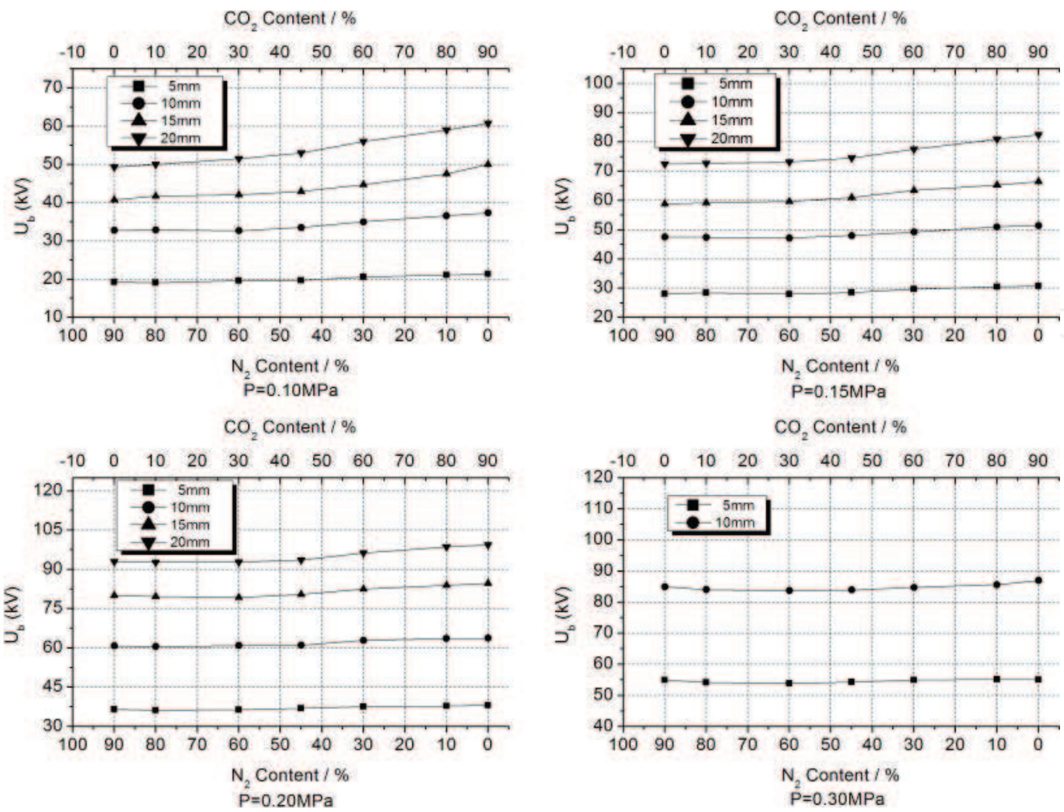

Figure 6. Relationship between AC-breakdown voltage and mixing contents of c-C_4F_8, N_2, CO_2 gas mixtures.

immediately, and even it has a trend to reduce a little. Only after the content of N_2 is lower than 30% and the content of CO_2 is higher than 60%, the breakdown voltage can increase significantly.

4. Power frequency AC-breakdown characteristics of the CF_3I, N_2, CO_2 gas mixtures

To CF_3I, it has been measured the breakdown characteristics for a constant content of 10% CF_3I and with different concentrations of N_2 and CO_2 under AC-voltage applied during the tests. The test method and experiment setup are similar to that in Section 2. The gas mixtures and mixing ratio are listed in **Table 1**. **Figures 7** and **8** show that under different air pressures, the variety of the AC-breakdown voltage applied and the maximum electric strength of the CF_3I, N_2, CO_2 gas mixtures as the gap changes. From **Figure 7**, it can be seen that the breakdown voltage of CF_3I gas mixtures gets higher as the electrodes gap gets bigger, but curves of different gas mixtures are more approached even closer compared with SF_6 and c-C_4F_8. The breakdown voltage of CF_3I gas mixtures has little difference with different contents of N_2 and CO_2. Moreover, N_2, which has better insulation strength, does not perform better than CO_2 when it is mixed with CF_3I. In **Figure 8**, the maximum electric strength of CF_3I gas mixtures has a trend to reduce as the electrodes gap increases, but the curves are smoother than c-C_4F_8, which shows that the sensitivity to the electric non-uniformity of CF_3I is lower than c-C_4F_8.

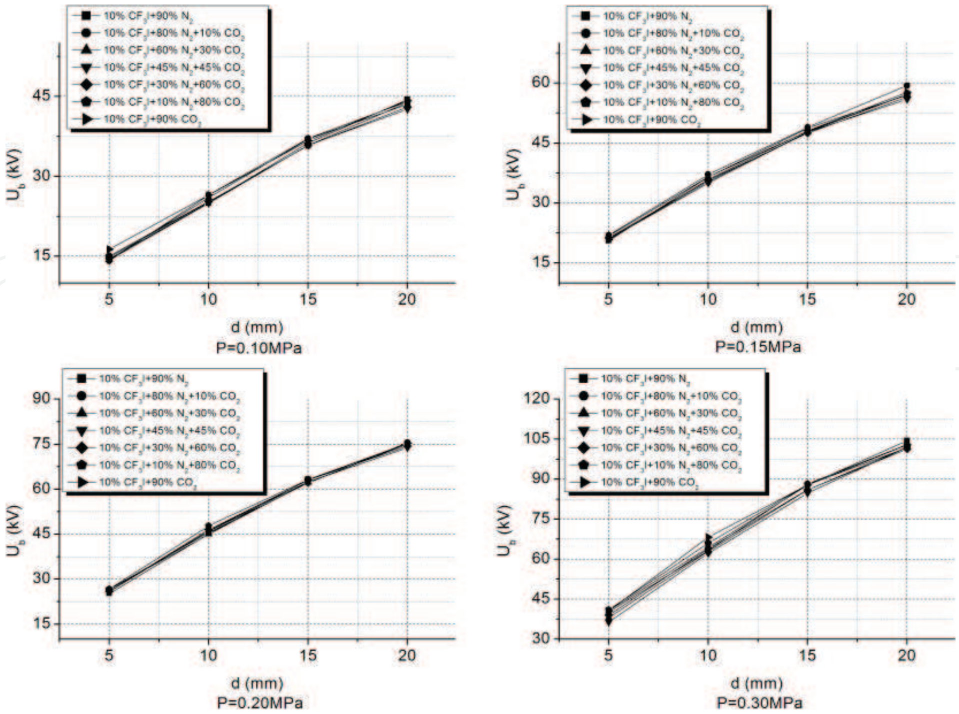

Figure 7. AC-breakdown voltage of CF_3I, N_2, CO_2 gas mixtures with different gas pressures.

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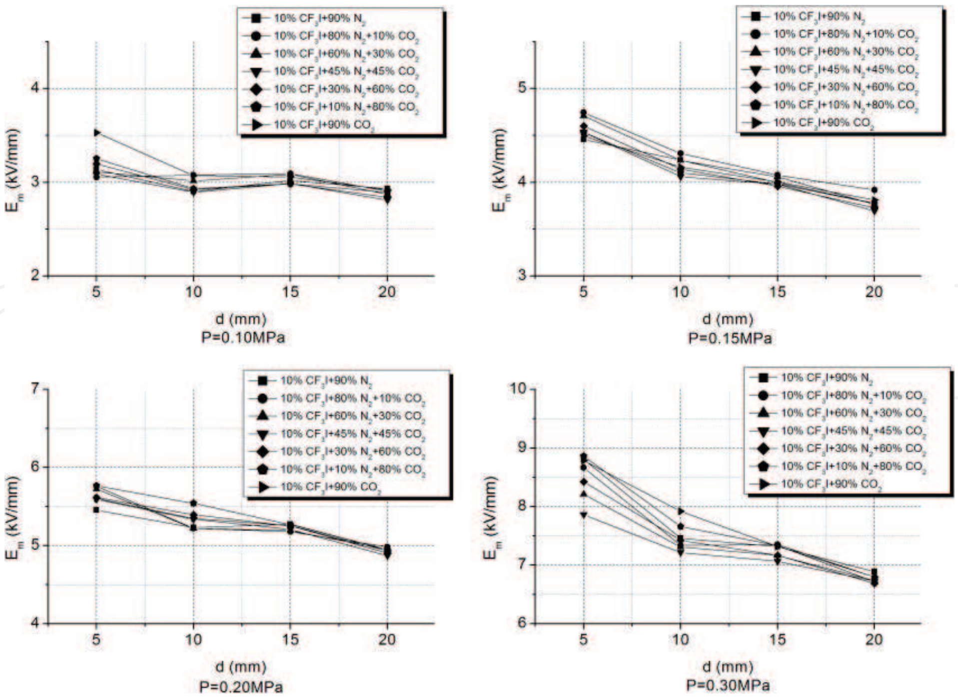

Figure 8. Maximum electric strength of CF_3I, N_2, CO_2 gas mixtures with different gas pressures.

Figure 9 shows, under different gaps of electrode, the variety of the AC-breakdown voltage for CF_3I, N_2, CO_2 gas mixtures as the gas pressure changes. Similar to the gas mixtures of SF_6 and c-C_4F_8, the AC-breakdown voltage increases linearly as the air pressure increases, and without

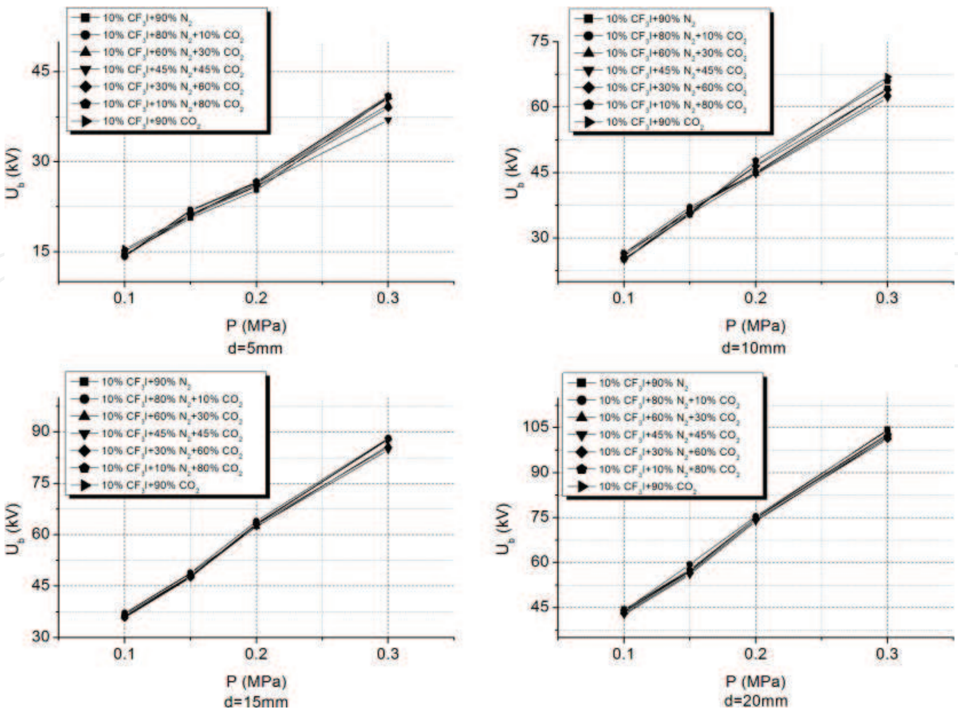

Figure 9. AC-breakdown voltage of CF_3I, N_2, CO_2 gas mixtures with different electrodes gap distances.

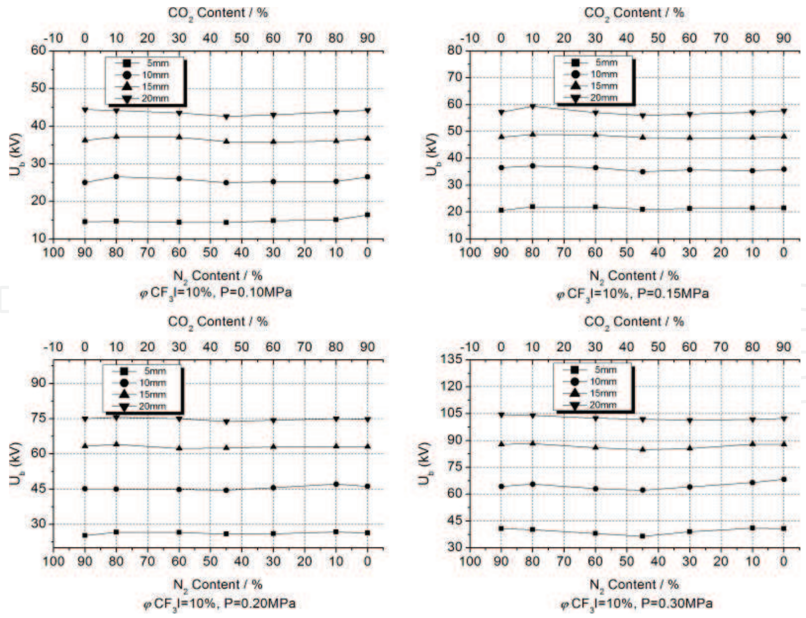

Figure 10. Relationship between AC-breakdown voltage and mixing contents of CF_3I, N_2, CO_2 gas mixtures.

hump effect or trend of saturation. Curves in **Figure 9** are similar to these in **Figure 7**, the superposition of the curves of gas mixtures with different contents is very high and the performed insulation characteristics are little different.

Figure 10 shows that under different gas pressures, the curves of the variety of the AC-breakdown voltage for CF_3I, N_2, CO_2 gas mixtures changes as the content changes. Generally, with the same mixing ratio of CF3I, the breakdown strength becomes stronger with the increasing ratio of CO_2. The same as the judge of the foregoing, the change of the gas mixtures of CF_3I is not obvious as the contents of N_2 and CO_2 change. What is worthy to be concentrated, it is that N_2 has higher insulation strength than CO_2, but it does not perform in the CF_3I gas mixtures.

5. Power frequency AC-breakdown characteristics of C_3F_7CN/CO_2

AC-breakdown characteristics of C_4F_7CN mixed with CO_2 are tested for different concentrations. **Figure 11** shows that AC-breakdown voltage of C_3F_7CN/CO_2 gas mixtures varies as the mixture ratio changes between 0 and 10% under different air pressures. Under the same gas pressure, as the mixture ratio of C_4F_7CN *k* increases, the AC-breakdown voltage of gas mixtures shows the saturated trend to increase. The lower the gas pressure is, the smaller the growth is. It has to be said that the influence of the mixture ratio *k* on the C_3F_7CN/CO_2 gas mixtures is less under low gas pressure. In addition, under high-gas pressure, increasing the mixture ratio k can increase the insulation properties of the gas mixtures. When the proportion of C_3F_7CN increases to 20%, the insulation properties of C_3F_7CN/CO_2 gas mixtures can approach that of pure SF_6 under the same condition.

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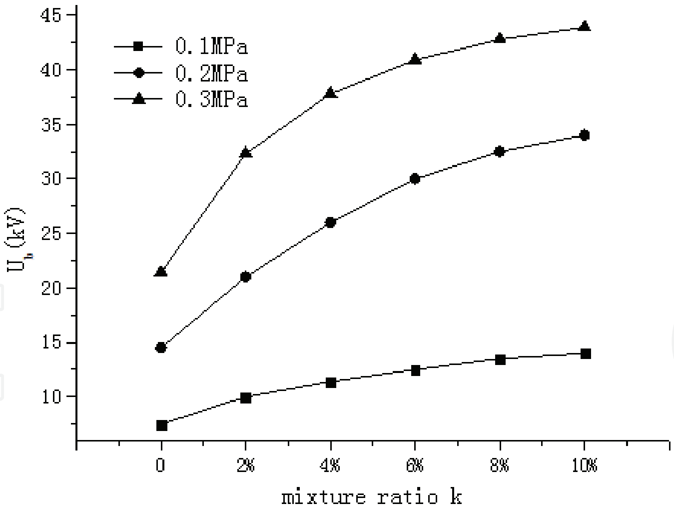

Figure 11. Relationship between power frequency breakdown voltage and mixture ratio of C_3F_7CN/CO_2.

6. Lightning impulse characteristics of c-C_4F_8, N_2, CO_2 gas mixtures

Figures 12 and **13** show the testing curves of the positive lightning impulse voltage of gas mixtures of 10% c-C_4F_8 with N_2 and CO_2. The positive lightning impulse voltage increases as the electrodes gap increases without the performance of the trend to saturation in SF_6 gas mixtures, and the breakdown voltage increases nearly linearly as the air pressure increases. From the perspective of the excitation energy and the ionisation energy of the microcosmic parameters, c-C_4F_8 is more appropriate to be mixed with CO_2 and the positive lightning impulse breakdown voltage of CO_2 is higher than N_2. According with **Figures 12** and **13**, it can be

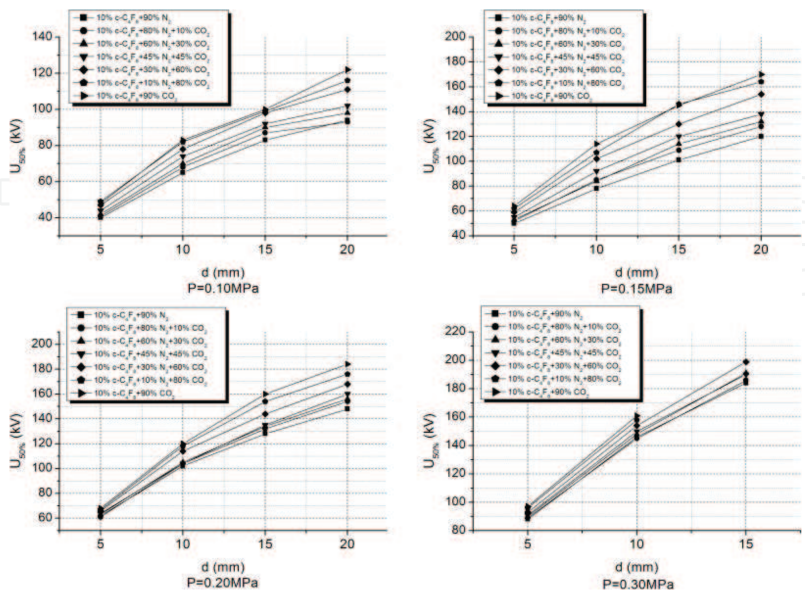

Figure 12. Positive lightning impulse breakdown voltage of c-C_4F_8, N_2, CO_2 gas mixtures with different gas pressures.

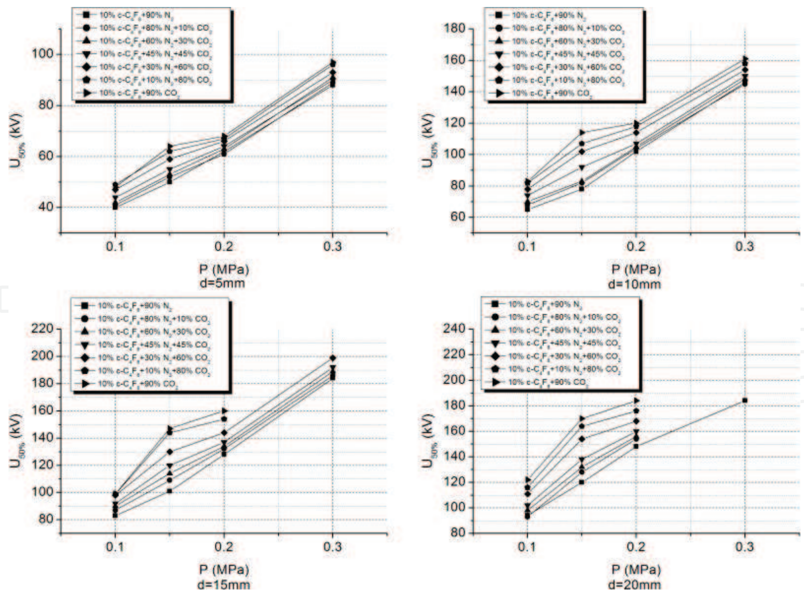

Figure 13. Positive lightning impulse breakdown voltage of c-C_4F_8, N_2, CO_2 gas mixtures with different electrodes gap distances.

seen that 10%c-C_4F_8 + 90%CO_2 gas mixtures have the highest breakdown voltage and 10%c-C_4F_8 + 90%N_2 gas mixtures have the lowest breakdown voltage.

Figure 14 shows the different curves of positive lightning impulse breakdown voltage of the gas mixtures of 10%c-C_4F_8 with N_2 and CO_2 as the content of N_2 and CO_2 changes. Because of CO_2 itself has stronger ability to tolerate positive lightning impulse and it will not have obvious ionisation with c-C_4F_8 compared with N_2, the breakdown voltage increases as the content

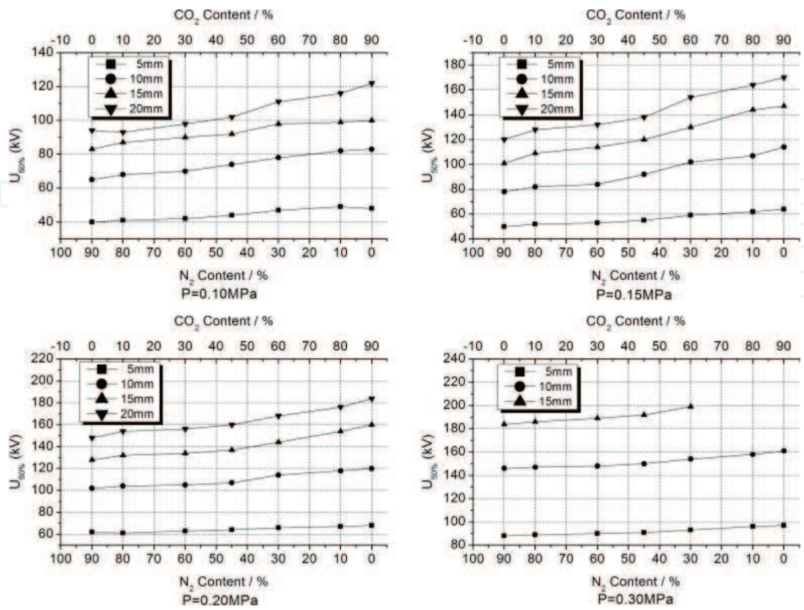

Figure 14. Relationship between positive lightning impulse breakdown voltage and mixing contents of c-C_4F_8, N_2, CO_2 gas mixtures.

of CO_2 in the gas mixtures increases. Because of the high resonance excitation, energy of N_2 in the gas mixtures will have negative impact on CO_2 when the content of N_2 exceeds 30%. The increase of breakdown voltage of the gas mixtures is not obvious, and when the content of N_2 is lower than 30%, the positive lightning impulse breakdown voltage shows more obvious trend to increase as the content of CO_2 increases. Comparing 10%c-C_4F_8 + 90%N_2 and 10%c-C_4F_8 + 90%CO_2, it is not hard to find that 10%c-C_4F_8 + 90%CO_2 has obviously higher positive lightning impulse breakdown voltage.

7. Lightning impulse characteristics of the CF_3I, N_2, CO_2 gas mixtures

Figures 15 and **16** show the curves of the positive lightning impulse (means that the impulse voltage is applied to sphere electrode, and the plane electrode is connected to ground) breakdown voltage of 10% CF_3I with N_2 and CO_2 of different contents. The positive lightning impulse voltage of CF_3I gas mixtures increases with a little saturation as the electrodes gap and air pressure increase. From the difference of breakdown voltages of gas mixtures with different contents and ratios, it can be seen that CF_3I has the similar properties with c-C_4F_8 and it is more appropriate to mix with CO_2.

Figure 17 shows the variation of the positive lightning impulse breakdown voltage of the gas mixtures consisting of 10% CF_3I and N_2 as well as CO_2 as the mixture ratio changes. The curves in **Figure 17** have the same change with the c-C_4F_8 gas mixtures, when the content of N_2 is lower than 30%, the excitation energy can weaken the ionisation of CF_3I and CO_2, and the breakdown voltage of the gas mixtures increases obviously and this is the same with the changing trend of c-C_4F_8 gas mixtures.

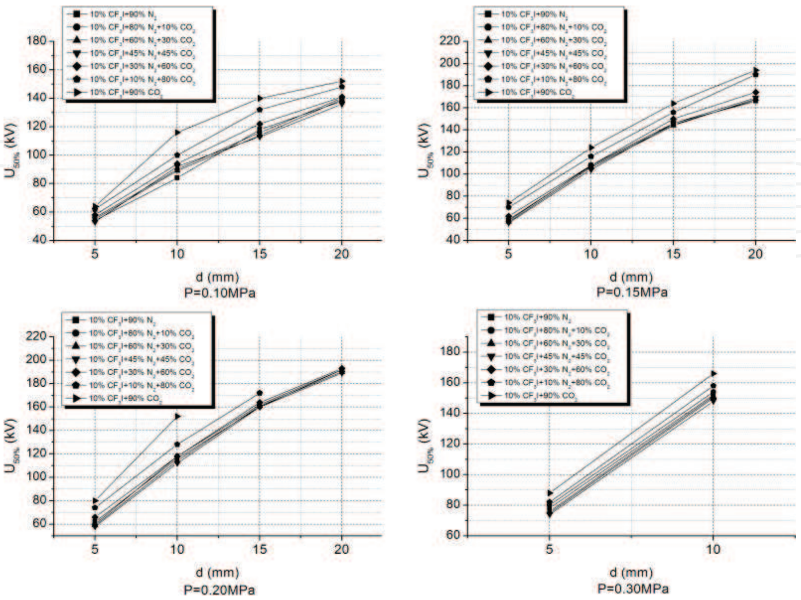

Figure 15. Positive lightning impulse breakdown voltage of CF_3I, N_2, CO_2 gas mixtures with different gas pressures.

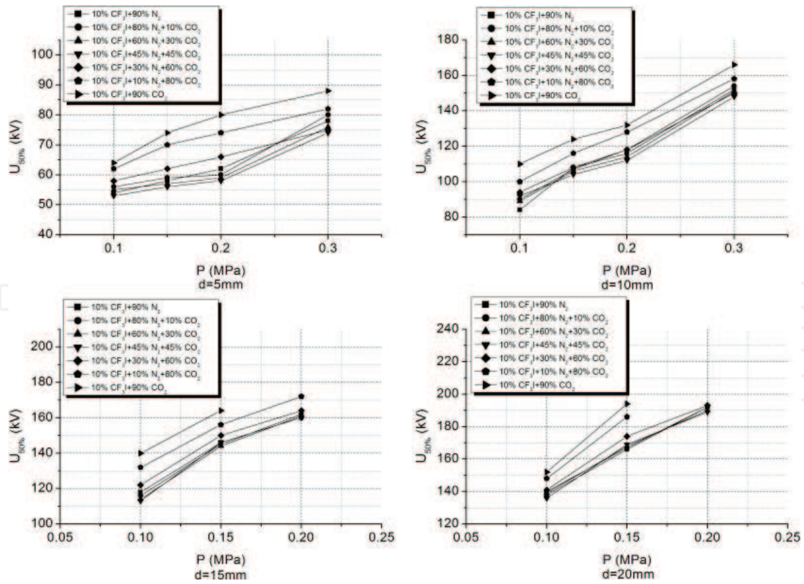

Figure 16. Positive lightning impulse breakdown voltage of CF_3I, N_2, CO_2 gas mixtures with different electrodes gap distances.

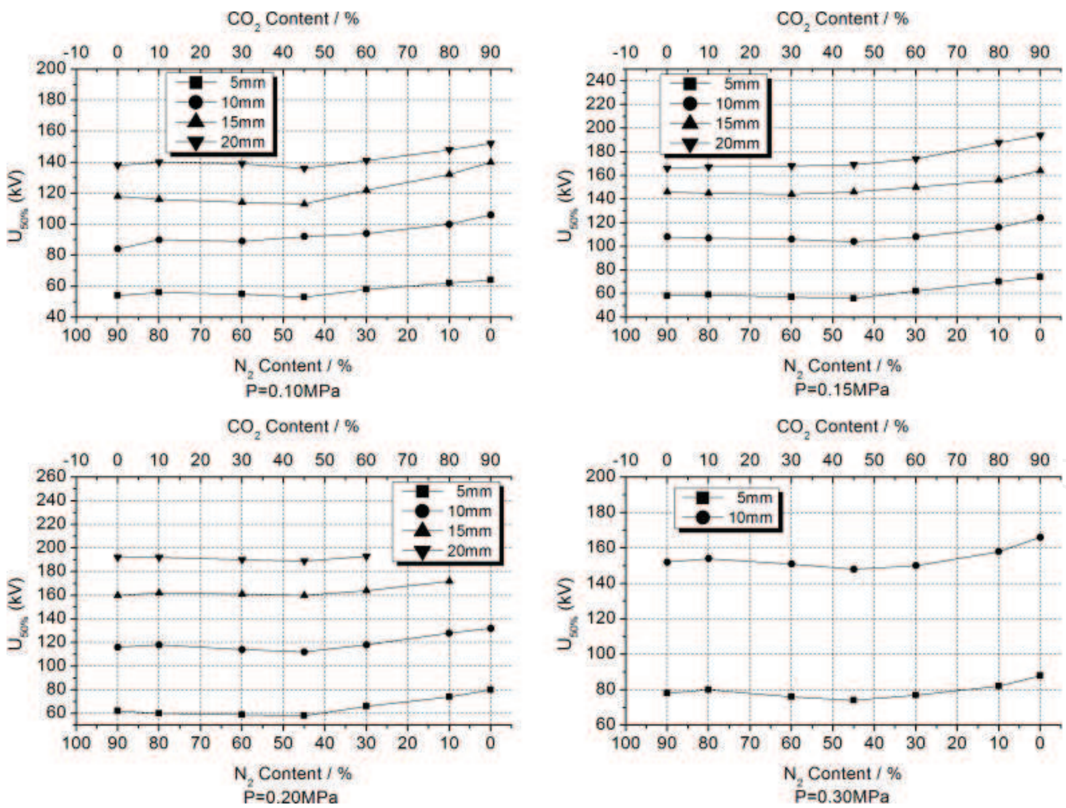

Figure 17. Relationship between positive lightning impulse breakdown voltage and mixing contents of CF_3I, N_2, CO_2 gas mixtures.

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8. Conclusion

1. In the consideration of insulation strength, c-C_4F_8 gas mixtures with N_2, CO_2 is prior than current SF_6/N_2 gas mixtures and pure SF_6. Moreover, c-C_4F_8 gas mixtures can solves the problem of c-C_4F_8 gas tending to liquefaction and carbon decomposition. Traditional c-GIS is widely used in the range of middle voltage, mainly in electric power substation and among consumers. Vacuum circuit breaker and grounded switchgear are both installed in a gas cavity shell, which is full with gas at 0.1–0.3MPa. Therefore, c-C_4F_8 gas mixtures can be applied to the gas switchgear of relative low voltage whose working pressure is low and function is not to break current arc, which can not only guarantee the insulation strength, but also greatly reduce the effect of insulation gas on the environment. Therefore, it has a good potential to substitute SF_6 and SF_6/N_2 as insulation media.

Moreover, for the areas with warm climate, electric apparatus such as transformer and high voltage power transmission wire are promising to use c-C_4F_8 gas mixtures as insulation media forming gas insulation transformer (GIT), gas insulation line (GIL) and cabinet Gas Insulated Switchgear at middle and low voltage (C-GIS).

2. Above comprehensive of analysis, under the same pressure conditions, the insulating strength of CF_3I is higher than that of SF_6 while ensuring CF_3I not to be liquefied. Compared with compressed air or compressed N_2 insulated in C-GIS, CF_3I can lower the pressure, in order to reduce the sealing technology and easy to manufacture. The shortcomings of high price also can be relief after mixed with buffer gas. Therefore, using CF_3I as insulating gas in C-GIS has better comprehensive performance than that of the present C-GIS.

CF_3I and N_2 mixed gas can be used as replacement of SF_6 gas in the C-GIS at a low pressure, which has bigger advantage on the dielectric strength, liquefaction temperature and cost, especially in 30% proportion of CF_3I in mixed gases, that is the most likely to be feasible.

As environmentally friendly insulation gas, CF_3I and its gas mixtures is a hot-topic on the global scope for gas insulating systems. The application of CF_3I and its gas mixtures in high-voltage apparatus not only meets the requirements and current trends on environmental protection in the international community, but also is a new direction in the field of electrical insulation.

To sum up, taking into account environmental characteristics, insulating properties and liquefaction temperature, CF_3I gas mixtures can be applied prior to C-GIS in the middle, low voltage system as well as GIL, GIT and other electrical devices in high-voltage system.

3. Power-frequency breakdown voltage of C_3F_7CN/CO_2 gas mixtures increases with the increase of mixing ratio from 0 to 10%. The relative dielectric strength of the gas mixtures showed a trend of saturated growth with the increase of mixing ratio, and power-frequency breakdown voltage of C_3F_7CN/CO_2 gas mixtures when C_3F_7CN is 8% ratio can reach 75% of that of pure SF_6 under the same condition. C_3F_7CN/CO_2 gas mixtures have potential of application of substitute for SF_6 in the electric power equipment, and the insulation of the other characteristics need further study. A deep insight into the partial discharge properties and corona stabilisation behaviour under strong inhomogeneous fields is needed for a full understanding.

Acknowledgements

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Appendix

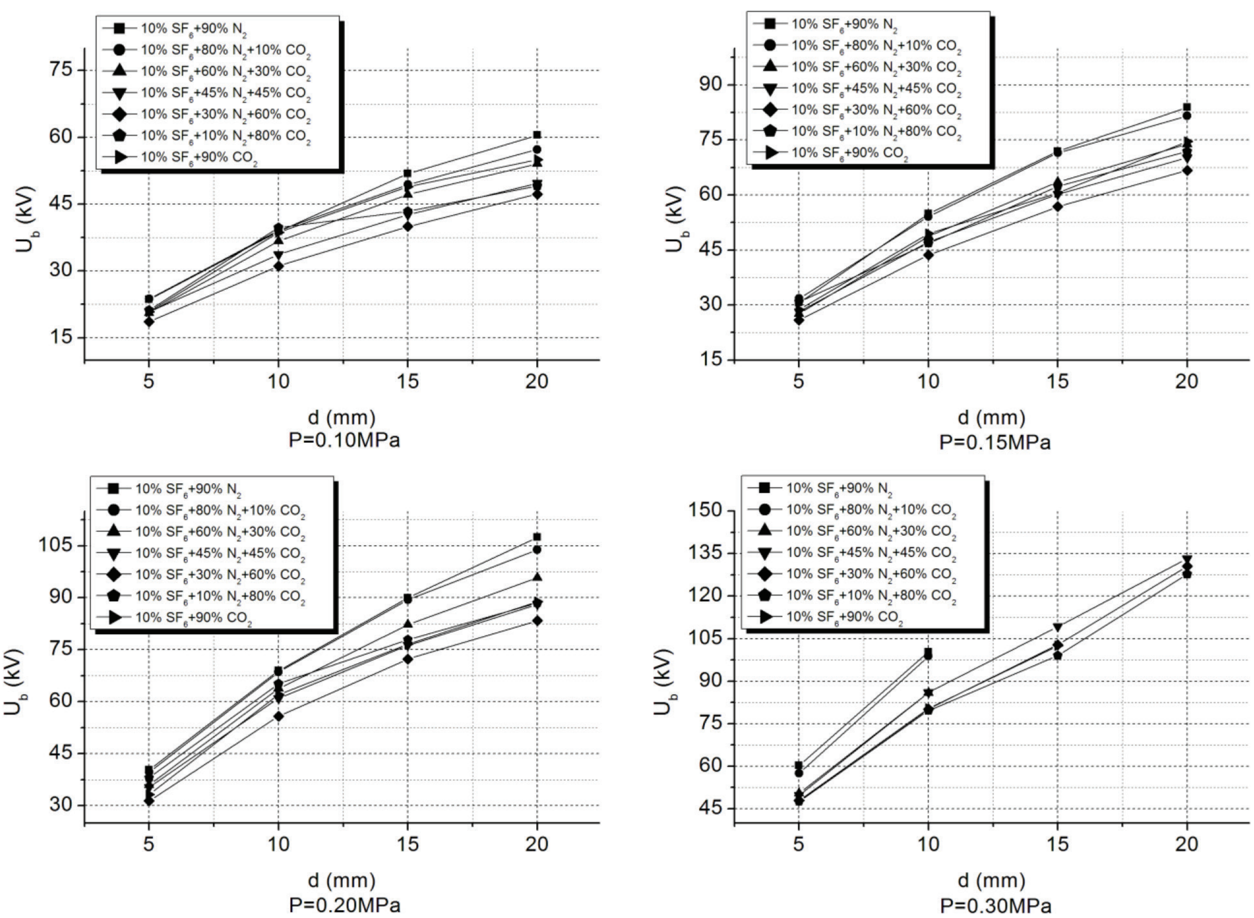

Figure A1. AC breakdown voltage of SF_6, N_2, CO_2 gas mixtures with different gas pressures.

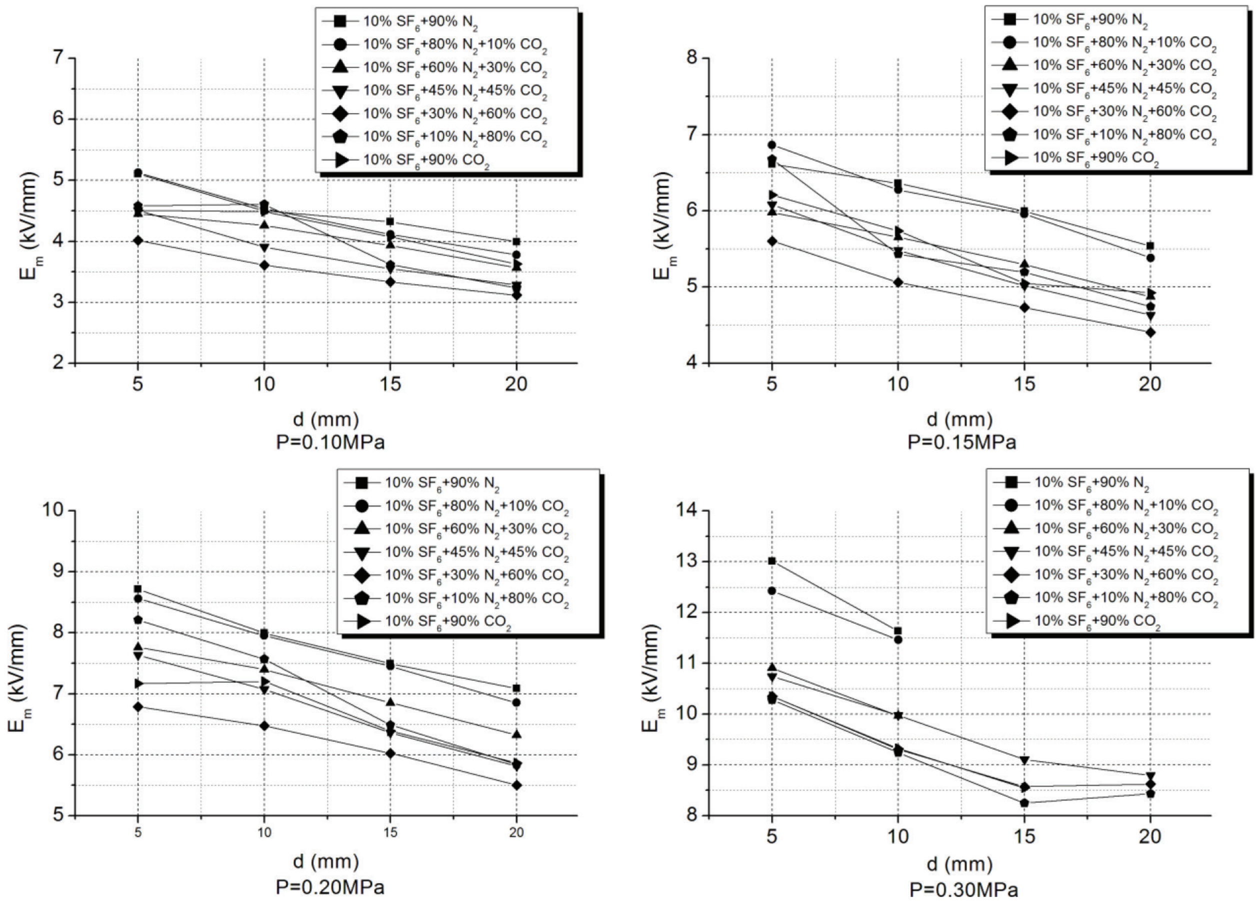

Figure A2. Maximum electric strength of SF_6, N_2, CO_2 gas mixtures with different gas pressures.

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References

[1] Yunkun D. Basic research of the environmentally friendly insulating gas CF_3I for its application in electric power apparatus [PhD thesis]. Shanghai: Shanghai Jiao Tong University; 2016

[2] Reilly J, Prinn R, Harnisch J, Fitzmaurice J, Jacoby H, Kicklighter D, et al. Multi-gas assessment of the Kyoto protocol. Nature. 1999;**401**:3466-3469

[3] Qingchen C, Yongxiang Z, Gao X, Wang M. Paris agreement: A new start for global governance on climate. Progress in Climate Change Research. 2016;**12**:61-67

[4] National Development and Reform Commission. China's Policy and Action on Climate Change 2017. Beijing: China Government; 2017

[5] WMO. The state of greenhouse gases in the atmosphere based on global observations through 2016. WMO Greenhouse Gas Bulletin (GHG Bulletin). October 2017;**13, 30**:1

[6] CE. Why Climate Policy-Makers can't Afford to Overlook Fully Fluorinated Compounds. Washington: World Resources Institute; 1995

[7] Xiangwan D. Opening a new stage of global green low-carbon development. China Awards for Science and Technology. 2016:6-6

[8] Dengming Xiao. Gas Discharge and Gas Insulation. China: Springer; 2016

[9] Wwvh W, Wwvl W, Connor JT, Astin AV, Engineerin SK. National Bureau of Standards. IRE Transactions on Aeronautical & Navigational Electronics. 2012;**2**:111-114

[10] Liu X, Wang J, Wang Y, Zhang Z, Xiao D. Analysis of the insulation characteristics of c-C_4F_8/CO_2 gas mixtures by the Monte Carlo method. Journal of Physics D: Applied Physics. 2008;**41**:015206

[11] Costello MG, Flynn RM, Bulinski MJ. Fluorinated nitriles as dielectric gases. Google Patents; 2013

[12] Nishimura H, Huo WM, Ali MA, Kim YK. Electron-impact total ionization cross sections of CF_4, C_2F_6, and C_3F_8. Journal of Chemical Physics. 1999;**110**:3811-3822

[13] Devins J. Replacement gases for SF6. IEEE Transactions on Electrical Insulation. 1980: 81-86

[14] Christophorou LG, Olthoff JK, Green DS. Gases for electrical insulation and arc interruption: Possible present and future alternatives to pure SF6. NIST TN-1425. 2011;**8**:391

[15] Xiao D, Zhu L, Li X. Electron transport coefficients in SF6 and xenon gas mixtures. Journal of Physics D: Applied Physics. 2000;**33**:L145

[16] Christophorou LG, Olthoff JK. Electron interactions with c-C4F8. Journal of Physical and Chemical Reference Data. 2001;**30**:449-473

[17] Zhao S, Jiao J, Zhao X, Zhang H, Xiao D, Yan JD. Synergistic effect of c-C_4F_8/N_2 gas mixtures in slightly non-uniform electric field under lightning impulse. In: IEEE Electrical Insulation Conference; 2016. pp. 531-534

[18] Wu B-T, Xiao D-M, Liu Z-S, Zhang L-C, Liu X-L. Analysis of insulation characteristics of c-C_4F_8 and N_2 gas mixtures by the Monte Carlo method. Journal of Physics D: Applied Physics. 2006;**39**:4204

[19] Macko WMJ. Toxicity review for Iodotrifluoromethane (CF_3I). In: Halon Options Technical Working Conference. US. 1999

[20] NFP Association. Standard on Clean Agent Fire Extinguishing Systems. In: NFPA 2001. New Orleans, LA, U.S.: Technical Committee on Halon Alternative Protection Options; 2000. p. 109

[21] De Urquijo J. Is CF_3I a good gaseous dielectric? A comparative swarm study of CF_3I and SF_6. Journal of Physics: Conference Series 86, 2007:012008

[22] Yun-Kun D, Deng-Ming X. The effective ionization coefficients and electron drift velocities in gas mixtures of CF_3I with N_2 and CO_2 obtained from Boltzmann equation analysis. Chinese Physics B. 2013;**22**:035101

[23] Kimura M, Nakamura Y. Electron swarm parameters in CF_3I and a set of electron collision cross sections for the CF_3I molecule. Journal of Physics D: Applied Physics. 2010;**43**:145202

[24] Cressault Y, Connord V, Hingana H, Teulet P, Gleizes A. Transport properties of CF_3I thermal plasmas mixed with CO_2, air or N_2 as an alternative to SF_6 plasmas in high-voltage circuit breakers. Journal of Physics D: Applied Physics. 2011;**44**:495202

[25] De Urquijo J, Mitrani A, Ruíz-Vargas G, Basurto E. Limiting field strength and electron swarm coefficients of the CF_3I–SF_6 gas mixture. Journal of Physics D: Applied Physics. 2011;**44**:342001

[26] De Urquijo J, Juárez A, Basurto E, Hernández-Ávila J. Electron impact ionization and attachment, drift velocities and longitudinal diffusion in CF_3I and CF_3I–N_2 mixtures. Journal of Physics D: Applied Physics. 2007;**40**:2205

[27] Xiaoxing Z, Junjie Z, Ju T, Song X, Yefei H."Experimental research on the partial discharge insulation properties of CF_3I/CO_2 and CF_3I/N_2 gas mixtures," Proceedings of the CSEE, vol. 34, pp. 1948-1956, 2014

[28] ZHAO Su, XIAO Dengming, ZHANG Hui, and DENG Yunkun, "Investigation on discharge polarity effect of CF_3I/N_2 gas mixtures under lightning impulse," Proceedings of the CSEE, vol. 37, pp. 3636-3642, 2017

[29] Li X, Zhao H, Wu J, Jia S. Analysis of the insulation characteristics of CF_3I mixtures with CF_4, CO_2, N_2, O_2 and air. Journal of Physics D: Applied Physics. 2013;**46**:345203

[30] Zhao X, Li B, Xiao D, Deng Y. Breakdown characteristics of CF_3I-N_2 gas mixtures in a needle-plate geometry. IEEE Transactions on Dielectrics and Electrical Insulation. 24 April 2017;**24**:869-875

[31] Xiao S, Cressault Y, Zhang X, Teulet P. The influence of Cu, Al, or Fe on the insulating capacity of CF_3I. Physics of Plasmas. 2016;**23**:123505

[32] Kochetov I, Napartovich A, Vagin N, Yuryshev N. Mechanism of pulse discharge production of iodine atoms from CF_3I molecules for a chemical oxygen–iodine laser. Journal of Physics D: Applied Physics. 2009;**42**:055201

[33] Kieffel Y. Characteristics of G3—An alternative to SF6. In: IEEE International Conference on Dielectrics; 2016. pp. 880-884

[34] Switzerland: ABB achieves breakthrough in switchgear technology with eco-efficient insulation gas. Tendersinfo News. 2014

[35] Rabie M, Franck CM. Assessment of eco-friendly gases for electrical insulation to replace the most potent industrial greenhouse gas SF_6. Environmental Science & Technology. 2017:369-380

[36] Stoller PC, Doiron CB, Tehlar D, Simka P, Ranjan N. Mixtures of CO_2 and $C_5F_{10}O$ perfluoroketone for high voltage applications. IEEE Transactions on Dielectrics & Electrical Insulation. 2017;**24**:2712-2721

[37] Zhao S, Xiao D, Jiao J, Zhao X. Discharge characteristics of c-C_4F_8/N_2 with and without insulator under standard lightning impulse. Presented at the IEEE Electrical Insulation Conference; 2016